Numerical Modeling of Magnetic Field Emissions from a Horizontal Directional Drilling Walk-Over Locating System

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Abstract

Walk-over locating technology is commonly employed to locate the drill head underground during horizontal directional drilling (HDD). In this paper, numerical modeling of the artificially induced magnetic field from a walk-over locator is presented. Numerical predictions are compared against the measured results and closed-form solutions to validate the model. After validations, the numerical model is used to investigate a situation that could affect the performance of a walk-over locator operated in a congested urban environment.

Keywords: HDD, walk-over, drill head tracking

1. Introduction

Horizontal directional drilling (HDD) is a popular construction technique employed in the construction industry to install utilities such as pipes, electrical and fiber optic cables underground [1]. During HDD, a borehole is first created in the ground using a piercing tool (drill head), and the utility to be installed is pulled back through this hole [2]. During drilling the drill head often deviates from its intended path unintentionally, and the operator steers it back. It's crucial to keep track of the drill head precisely so that it could be steered accurately, avoid accidental damage to other buried utilities [3], and generate accurate 'as-built' records for record keeping and sustainable use of the congested underground space. Several methods have been investigated in the past for locating the drill head while drilling including the use of inertial sensors like accelerometers & gyroscopes [4], magnetometers that measure the earths naturally occurring magnetic field [5], wire-line locating systems that use the magnetic field created by a charged surface wire [6], and walk-over locating systems [7]. Walk-over technique is a commonly used technique to locate and track the drill head (in HDD lingo, locating and tracking are considered as two different goals). In this technique, a dipole transmitter called as 'sonde' (or beacon) is placed within the metallic casing of the drill head, and the artificially created magnetic field is measured at the surface using a handheld receiver from which co-ordinates of the cutting tool is estimated.

Sonde is a battery operated device that emits magnetic field using a ferrite loaded solenoid antenna. It operates at frequencies anywhere from few kHz to around 80 kHz [7] depending upon the boring depth required. These frequencies are selected to minimize the attenuation of field through soil. Several kinds of receivers have been developed over the years and they are generally classified into two types, namely, single axis (SA) receivers and vector sum (VS) receivers. SA receivers measure one of the three vector components (B_x, B_y and B_z) of magnetic field at a time. During its operation an operator scans the surface and identifies the peak signal response manually. At this point the depth is calculated as a function of signal strength. A SA receiver consists of two single axis antennas which are separated by a vertical distance *(w)*. Field strengths $(B_1 \,\&\, B_2)$ at two heights are recorded from which the depth(d) is calculated as [7]:

$$d = \frac{w}{\left(\frac{B_1}{B_2}\right) - 1}. \qquad (1)$$

Since SA receivers cannot pick up more than one component at a time, the so called 'ghost signals' are often detected resulting in false peak responses [8]. To rectify this problem, advanced VS receivers measure all three components from which the total field strength is calculated.

Simplified closed-form solution of a current loop is often used to predict the field emanating from a sonde [9, 10]. However, these solutions are limited to ideal conditions. Often, the presence of other emitters and large ferrous objects in the vicinity of a locator, especially, in an urban setting creates interferences which affect the performance of these devices. A detailed modeling is necessary to understand these interactions so that their performance could be improved. In this paper, a detailed numerical modeling of a HDD walk-over locating system is presented. A section of HDD drill head with a sonde is numerically modeled using COMSOL Multiphysics, and the results obtained are compared against measured data and closed-form solutions to validate the model. Following validations, the numerical model is used to simulate a particular scenario where the presence of a large metallic object near a walk-over locator could interfere with its operation, and cause errors in depth estimation.

2. Use of COMSOL Multiphysics

2.1 Mathematical description

Numerical model was created using the AC/DC module with magnetic fields interface. Since the wavelength involved here are very large (wavelength of a 32 kHz sinusoidal signal in air is over 9 km long) compared to the physical size considered in the model (few meters wide) quasi-static assumptions are made. A typical sonde, while creating the magnetic field for locating purpose, also uses it to transmit data from other onboard sensors like inclinometers to the surface using radio communication techniques. For example, emissions from a commercial sonde operating at 32 kHz were recorded, and its Fourier spectrum revealed several distinct frequencies in addition to the main operating frequency with few hundred hertz offset. However, during modeling, only the main operating frequency was considered. Magnetic vector potential (A) is solved in the frequency domain using the following governing equation:

$$(j\omega\sigma - \omega^2\epsilon_0\epsilon_r)A + \nabla \times (\mu^{-1}\nabla \times A) = J_e \quad (2)$$

where ω is the angular frequency, σ is the electrical conductivity, ϵ_r is the relative permittivity, ϵ_0 is the permittivity of free space, μ is the permeability and J_e is the source current density. Source is a current driven ferrite loaded solenoid coil with J_e given by the following equation:

$$J_e = \frac{N\,I}{A} \quad (3)$$

where N is the number of turns in the coil, I is the coil current and A is the cross-sectional area of coil. Magnetic insulation is prescribed for the external boundaries (tangential components of A are set to zero) according to the equation:

$$n \times A = 0 \quad (4)$$

2.2 Model description

During HDD operation, a cutting tool is pushed (and rotated) through the ground from a launching pit using surface launched rig. As the cutting tool proceeds forward, short sections of metallic pipes are attached to the tool which forms a continuous pipe that transport drilling fluid to the cutting edge and transmit the mechanical forces involved. This drill pipe could run tens of meters long depending upon the length of borehole required, and sonde is placed in the front just behind the cutting edge. In the numerical model, only a short section of this drill pipe and drill head is modeled so that the computational requirements are kept within the available resources. A photograph of the drilling head (8cm in diameter and 1m in length) used in this work is shown in Figure 1 along with its CAD model created using COMSOL. Figure 2 presents a simplified sketch of the model. As seen in Figure 2, sonde is modeled as a ferrite loaded solenoid coil suspended within a longitudinal cavity in the drill. The cavity is covered by a lid which has slots cut open to let the fields pass through. Parameters of the current driven coil are based on an actual sonde used in the experiments (described in the next section). The multi-turn coil was modeled using the Coil Geometry Analysis tool. Actual source current was measured at the terminals and used as an input for the model in order to calculate J_e. The relative permeability of materials present in the model is given in Table 1. In practice, drilling can take place within inhomogeneous soils with a wide range of electrical conductivity and permittivity. Since the signal transmission considered here is magnetic, soil permeability is the property of interest. For most soils permeability can be assumed to be unity, except, in rare cases [5]. Thus, unit permeability was used for medium surrounding the drill. Entire model is enclosed within a sphere that is 7m in diameter and terminated using magnetic insulation boundary.

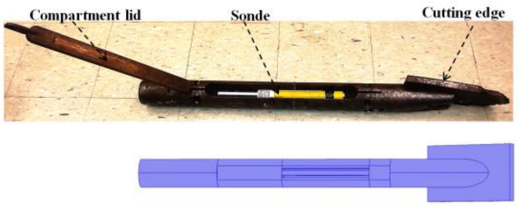

Figure 1. Photograph of a sonde placed inside the drill head (top); CAD model created using COMSOL (drill head compartment lid is left open to show the insides).

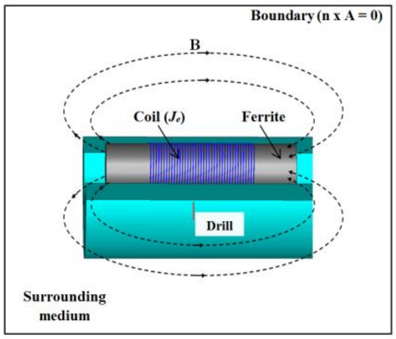

Figure 2. A simplified sketch of the numerical model.

Table 1. Material Parameters used during modeling

Material	Relative permeability
Drill	4000
Ferrite	600
Surrounding medium	1

2.3 Mesh generation

Numerical model was discretized using the free tetrahedral mesh generator. Three levels of mesh densities from fine to extra finer elements were used to discretize the surrounding medium, the drill and the sonde, respectively. A mesh refinement study was carried out by systematically reducing element sizes till the results did not show any significant changes. Final mesh consists of ~923k elements ranging from 1 mm to 288 mm. Figure 3 shows the discretized model. The model was executed on a multi-core workstation which occupied over 42 GB of RAM and solved ~600k degrees of freedom.

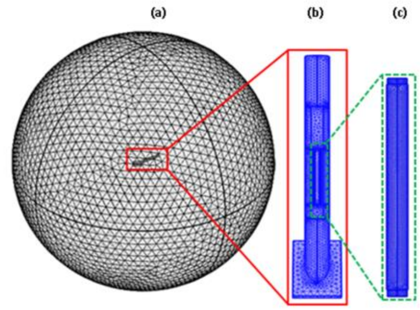

Figure 3. Mesh generated from the model: (a) fine mesh for medium surrounding the drill, (b) finer mesh for the drill head, and (c) extra fine mesh for the sonde.

3. Experimentation

Numerical results were compared against the experimental data to validate it. In order to give full control over the measurements a custom sonde and a receiver was fabricated for this study. Schematic diagram of the experimental setup is shown in Figure 4. The transmitter produced a sinusoidal signal at 32 kHz and it was radiated by a ferrite loaded antenna (1.2 cm in diameter and 19 cm in length) with 266 turns of Litz wire. Sonde was placed inside the drill compartment (shown in Fig 1) and it was suspended in an open space in order to minimize external interferences. In the numerical model, medium surrounding the drill was given unit permeability, and experiments were also conducted in free space for a direct comparison. Magnetic field generated by the transmitter was measured by sweeping the space around drill with a 3-axis receiver. Three ferrite loaded orthogonally situated coils tuned at 32 kHz were used to record the vector components of magnetic field in Cartesian coordinates. Analog signals from individual receive antennas were sequentially routed through a multiplexer controlled by a microcontroller, and it was later amplified using an instrumentation amplifier and filtered by a programmable bandpass filter. Finally, the signals were digitized using a digital storage oscilloscope (Picoscope 5000 series) connected to a PC. Magnetic flux density was then calculated from the recorded voltages for each component, and the magnitude of B-field was calculated as $\sqrt{B_x^2+B_y^2+B_z^2}$. Data was collected in longitudinal and transverse planes centered on the sonde for distances of up to 2m away from the drill. In a plane located transverse to the sonde's longitudinal axis magnetic field was recorded in a circular arc at two radial distances (1.5m and 2m).

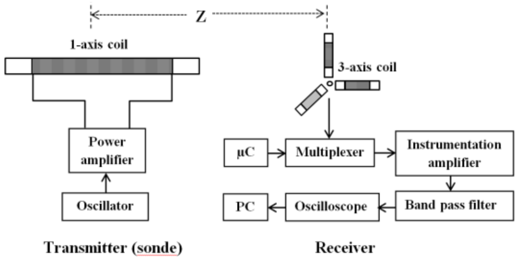

Figure 4. Schematic diagram of the experimental setup.

4. Results and Discussion

In this section, results predicted by the numerical model are compared against the closed-form solutions [5] and measured data. Figure 5 shows the numerically calculated contour plot of magnetic flux density (B) around the drill. A close-up view of the field across the drill in transverse and longitudinal planes is shown in Figure 6. As shown, the contour lines generated by the sonde undergo distortion close to the drill. However, after moving a certain distance away contour lines resembles the field from a solenoid. Figure 7 shows the comparison of B for a 90-degree arc in a transverse plane at two radial distances obtained from numerical, analytical and experimental methods. As seen from this chart the results from all three methods show good agreement. A similar result in longitudinal plane is also presented in Table 2, which shows good match between the results as well.

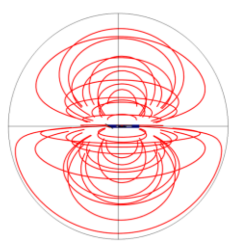

Figure 5. Screenshot from the COMSOL model showing magnetic field lines emanating from the drill.

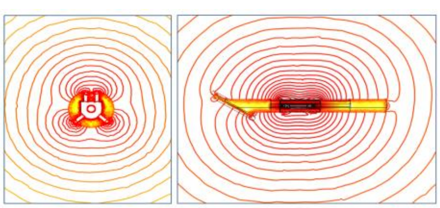

Figure 6. Screenshot from the COMSOL model showing B-field in transverse (left) and longitudinal (right) planes around the drill.

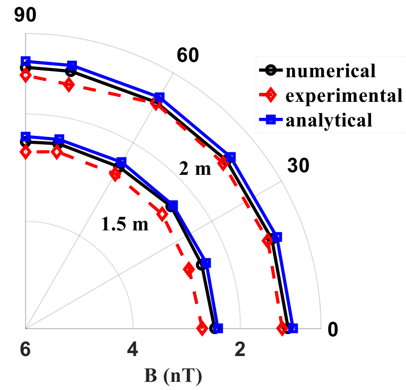

Figure 7. Polar plot of magnetic flux density transverse to the drill at three radial distances obtained from numerical, analytical and experimental methods.

Table 2. Comparison of B-field in a longitudinal plane

Dist. (m)	Angle (degrees)	Numerical (nT)	Analytical (nT)	Measured (nT)
1.5	0	3.28	3.82	4.02
	20	3.24	2.34	3.28
	40	2.53	2.92	3.14
	60	2.72	3.69	2.30
	80	2.58	1.95	3.29
	90	2.52	2.42	3.60
2.0	0	1.15	1.61	1.43
	20	1.15	0.99	1.61
	40	1.13	1.23	1.06
	60	1.12	1.56	0.98
	80	1.12	0.82	0.68
	90	1.14	1.02	1.21

Next, the coil parameters - inductance (L), reactance (X_L) and impedance (Z) - were measured using an impedance analyzer at 32 kHz, and the results were compared against numerical calculations for two different cases. In the first case, measurements were made after removing the sonde away from the drill. Under this scenario, its inductance can be obtained using the following equation [6]:

$$L = \frac{\mu_0 \, \mu_{rod} \, A \, N^2}{l} \quad (5)$$

where N is the number of turns, μ_{rod}, A and l are the effective permeability, cross-sectional area and length of the ferrite rod, respectively. Comparison of three coil parameters for the first case is shown in Table 1. Next, the sonde was dropped into the drill, and measurements were repeated. Coil parameters for the second case are shown in Table 4. As seen from these tables, the numerically calculated values showed good agreement with the measured data for first case.

A slight discrepancy is seen in the second case which could be attributed to several factors including the skin effects and proximity to the drill.

Table 3. Coil parameters when sonde is away from the drill

Parameter	Measured	Analytical	Numerical
L (mH)	4.61	4.80	5.20
X_L (Ω)	926	964	1059
Z (Ω)	927	965	1060

Table 4. Coil parameters when sonde is inside the drill

Parameter	Measured	Numerical
L (mH)	3.86	2.50
X_L (Ω)	776	455
Z (Ω)	784	459

5. Performance of a locating system due to magnetic interference

Following validations, the numerical model was used to simulate a specific case that could influence the performance of a walk-over locating system in practice. Often the presence of other emitters in the area such as high voltage overhead powerlines [12] could interfere with the magnetic field produced by sonde, especially, in a congested urban environment. Objects such as rebar under a concrete pavement and other ferrous objects located nearby could also affect the measurements. While this numerical model could be used to simulate some of those scenarios, in this paper, one particular case is investigated. A solid ferrous block (60cm x 30cm x 30cm) is assumed to be near the receiver and its influence on the received magnetic flux density was calculated. A parametric sweep of the horizontal distance (D) between receiver and the box (Figure 8) was conducted with drill resting 2m directly beneath the receiver. Variation of magnetic flux density at the receiver with increasing distance D is shown in Figure 9. As seen in that graph the flux density drops significantly as the object moves closer to the locator due to strong coupling of the field with object. This could result in erroneous results during depth estimation using equation 1. Similar study could also be conducted to understand the influence of other factors that interfere with the magnetic field.

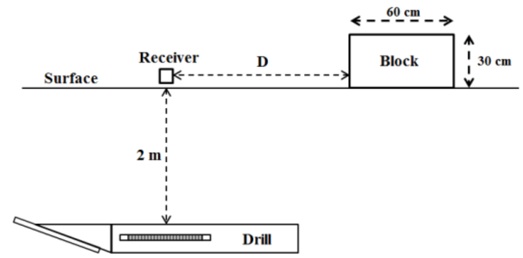

Figure 8. Setup used to study the influence of objects near a walk-over locating device.

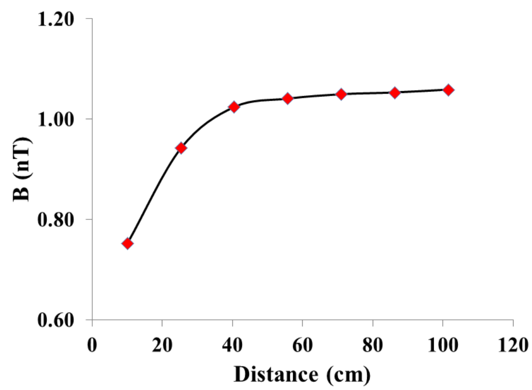

Figure 9. Variation of flux density at the receiver for increasing distance D.

6. Conclusion

In this paper, numerical modeling of magnetic emissions from a HDD walk-over locating system is presented. Numerical predictions were compared against the experimental and closed-form solutions, and good agreement between all three results was observed. Following the validations, numerical model was used to simulate a specific case that could influence the performance of a walk-over locating system in practice. Numerical model presented here could be used to simulate and understand the effects of external factors that could affect the performance of these locators in a congested urban environment.

7. References:

1. H.J. Bayer, *HDD practice handbook*, Vulkan-Verlag GmbH, (2004).
2. D. Willoughby, *Horizontal Directional Drilling*, pp. 1-263. Mcgraw-Hill, New York (2005).

3. A. Jaganathan, J.Shah, E.A. Allouche, et al., "Modeling of an Obstacle Detection Sensor for Horizontal Directional Drilling Operations", *Automation in Construction*, vol.20, pp.1079-1086 (2011).
4. A.S. Jurkov, et al., "Experimental feasibility of the in-drilling alignment method for inertial navigation in measurement-while-drilling" *IEEE Transactions on Instrumentation and Measurement*, vol.60**,** no.3, pp.1080-1090 (2011).
5. T. Torkildsen, I. Edvardsen, A. Fjogstad, A. Saasen and T. Omland. "Drilling fluid affects MWD magnetic azimuth and wellbore position", *Proc. SPE/IADC Drilling Conf.*, pp.595-602 (2004).
6. Paratrack 2 tracking system. http://www.vectormagnetics.com/horizontal-directional-drilling/products/paratrack-2-tracking-system [Visited: 1/9/2016].
7. J. E. Mercer, "Walk-over locating technology", *No-Dig 2000 Conference,* Perth, Australia (2000).
8. Operator's manual for TK series guidance system, Subsite electronics. http://subsite.com/uploads/053-2832%20TK%20Series%20rev1-0.pdf [Visited: 1/9/2016].
9. J. E. Mercer. "Locating systems for horizontal directional drilling." *No-Dig Engineering* 4.5 (1998): 2-4.
10. M. F. Gard. "Magnetic field sensing in the underground construction environment", *Sensors for Industry Conference, 2002. 2nd ISA/IEEE*. IEEE, (2002).
11. R.H.M. Poole, "Ferrite Rod Antennas for HF", WHP 091, BBC, U.K (2004) www.bbc.co.uk/rd/publications/whitepaper091[June 5, 2016].
12. E.V. Hinueber, (iMAR Navigation). "Most accurate drilling guidance by dead-reckoning using high precision optical gyroscopes", *Proceedings No Dig Conference of Horizontal Directional Drilling*, Brisbane (2006).

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